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INFRARED TECHNOLOGY AND NONDESTRUCTIVE TESTING

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REDSTONE ARSENAL, ALABAMA

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INFRARED TECHNOLOGY AND NONDESTRUCTIVE TESTING

By

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ABSTRACT

This report presents infrared technology in general and its relation to the nondestructive testing of solid fuel rocket motors, primarily for unbond flaws. Various projects by government contractors concerning the use of IR techniques and instrumentation for unbond flaw detection are reviewed.

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I. INTRODUCTION

One of the most recent areas of technology being developed in the compass of the nondestructive testing of missiles is that of infrared. The Defense Department has let several contracts for investigations in the application of infrared techniques to the problem of missile quality determination. A suitable production line instrumentation setup is especially needed.

In solid propellant rocket motors, unbonding between the various laminated layers (fuel to liner, liner to case, etc.) can adversely affect the performance of the motors. This condition appears to be one of the most difficult to detect with present nondestructive testing equipment.

Recent developments indicate that infrared technology may be especially useful for bond quality determination. In one technique, heat energy is to be injected into the motor case at a specific area and measurements made of the infrared (IR) energy emitted. The fluctuations of the emitted IR caused by an area of unbond form the basis of detection. Other techniques make use of the natural radiation emitted by the missile case. This subject will be covered in Section X.

In this report a survey of the state-of-the-art of IR technology is presented along with components and techniques which might be of use in developing a device for the inspection of solid fuel rocket motors.

II. BASIC PHYSICS

All electromagnetic radiation travels with the same velocity (c) and can be considered as transporters of energy; however, their interactions with matter and their methods of excitation differ widely.

Emitted electromagnetic radiation can be broken down into two classes based on the different ways in which it is produced. Continuous radiation is due to the random thermal motions of the atoms and molecules. Characteristic radiation, which gives rise to either line spectra or band spectra, are due to the orbital transitions of the electrons and vibrations of the molecules. In general, the emitted light energy has a spectrum dependent on the surface temperature of the substance and its inherent surface properties.

Infrared radiation is the portion of the electromagnetic spectrum just above that of the visible wave lengths, and spans a wave length range from about 0.78 microns (μ) to 1000 μ. It is commonly divided arbitrarily into three segments or regions. For example, the near IR region is for wave lengths from 0.78 μ to 1.5 μ; the intermediate or middle IR region from 1.5 μ to 5.6 μ; and the far IR region is from 5.6 μ to 1000 μ. This emitted electromagnetic or radiant energy in a direct function of the temperature, and thus any body above absolute zero emits radiation in the IR region of the spectrum.

Incident electromagnetic radiation on a surface is absorbed, reflected, and transmitted (in general, combinations of these processes occur). The absorption may change with wave length, but for many materials it is constant over a fairly wide range. Kirchoff, in the early 1850's, deduced his famous Radiation Law for all electromagnetic radiation. It stated that good radiation absorbers are good radiation emitters and that poor radiation absorbers are poor radiation emitters. A theoretical surface with maximum efficiency, i.e., one that absorbs all of the incident radiation, is said to be a blackbody. It is consequently in thermal equilibrium and emits energy at the same rate. Of course not all radiation is blackbody for all bodies are not equally as efficient. Because of this there is a factor called emissivity (sometimes radiant emissivity) which enters into all equations relating to radiation intensity measurements. Emissivity is defined as the ratio of "emitted" radiant power to the radiant power from a blackbody at the same temperature.

There has been much theoretical work done to explain the nature of the spectral distribution curves for blackbodies (Figure 1). Wien made the discovery that for a blackbody, the product of the temperature and the maximum value of the wave length is a constant, hence the peaks of the blackbody curves move to the right (increasing wave length) with decreasing temperature. The Stefan-Boltzmann Law states that the total radiation emitted by a blackbody is proportional to the fourth power of the temperature. In general,

$$W = \epsilon \sigma T^4$$

where

W = total radiation emitted in watts per cm^2

ϵ = emissivity (= 1 for blackbody)

$\sigma = 5.669 \times 10^{-12} \frac{\text{Watt}}{(\text{cm})^2 (^\circ\text{K})^4}$ —(Stefan-Boltzmann constant)

T = temperature in $^\circ$K.

The above laws were deduced from classical thermodynamics however, and the classical methods failed to adequately describe the blackbody spectral curves. It was not until Planck made use of his quantum mechanics that the correct formula for these curves was established.

The formula for the radiant power or rate at which IR radiation is emitted was developed from his quantum-mechanical study of systems in

thermal equilibrium, i.e., blackbody sources, and is named Planck's Law. It is

$$H(\lambda T)d\lambda = \frac{c_1}{\lambda^5}\left[\frac{d\lambda}{e^{c_2/\lambda T} - 1}\right]\frac{\text{watt}}{(\text{cm})^2 \cdot 2\pi \text{ ster})}$$

where

$H(\lambda T)$ = radiant flux density emitted by the surface

c_1 = 3.741×10^{-12} watt-(cm)^2

c_2 = 1.439 cm-deg

λ = wave length, cm

T = temperature in $^\circ$K

e = base of Napierian logarithms.

Both Wien's Law and the Stefan-Boltzmann Law can be derived directly from Planck's Law, with suitable approximations.

Another property of radiation is that its intensity at a given distance follows the inverse square law, i.e., the intensity of radiation emitted from a "point" source varies inversely as the square of the distance between source and receiver.

The theory just presented is worked out in detail in a number of textbooks.

III. THE IR SYSTEM

All IR systems include a source, the intervening environment between source and detector, optics, an IR detector, and an output for suitable presentation.

The system is generally classified as either passive or active. The passive IR system detects the radiation that is naturally emitted by the target (or source) and the active system employs artificial means to illuminate or heat the target which then radiates the IR energy back to the detector. Usually the active system target radiation is chopped with a reticle or chopper to provide an alternating signal that is useful for amplification.

The optical system focuses the incoming radiant energy on the detector with minimum transmission losses. It also filters out unwanted radiation from surrounding sources. The detector is an energy

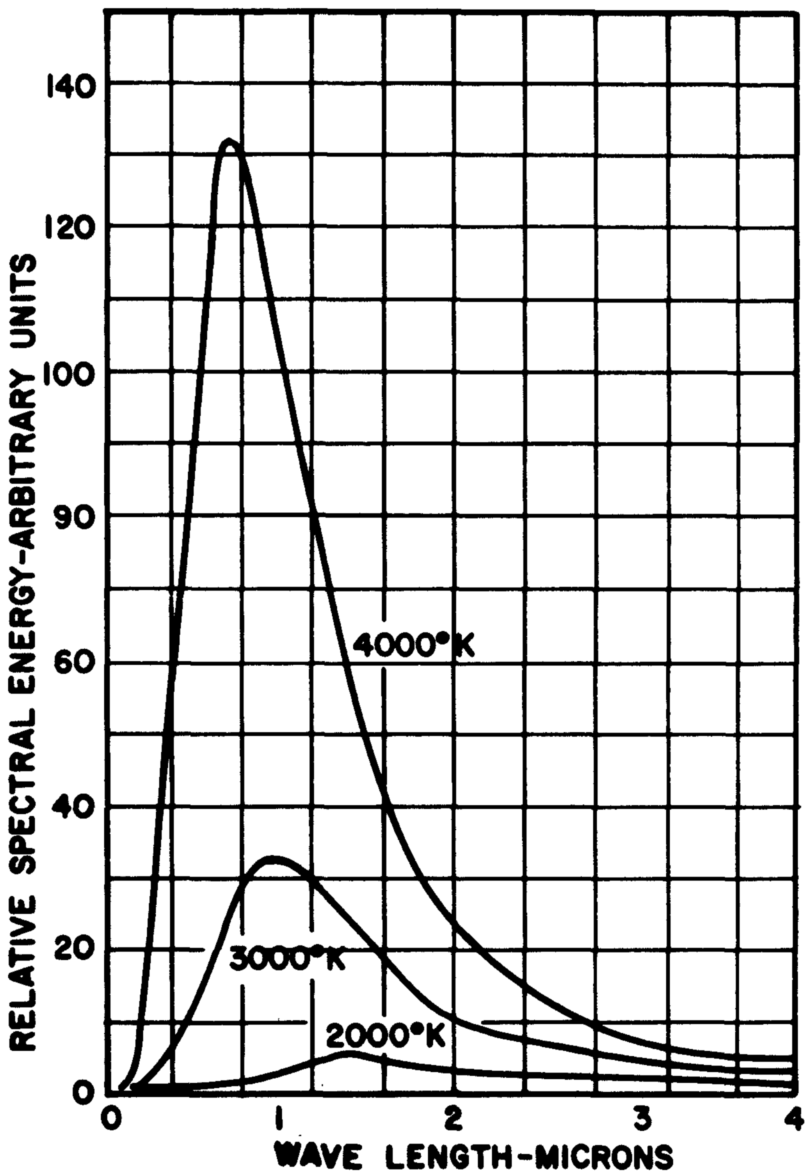
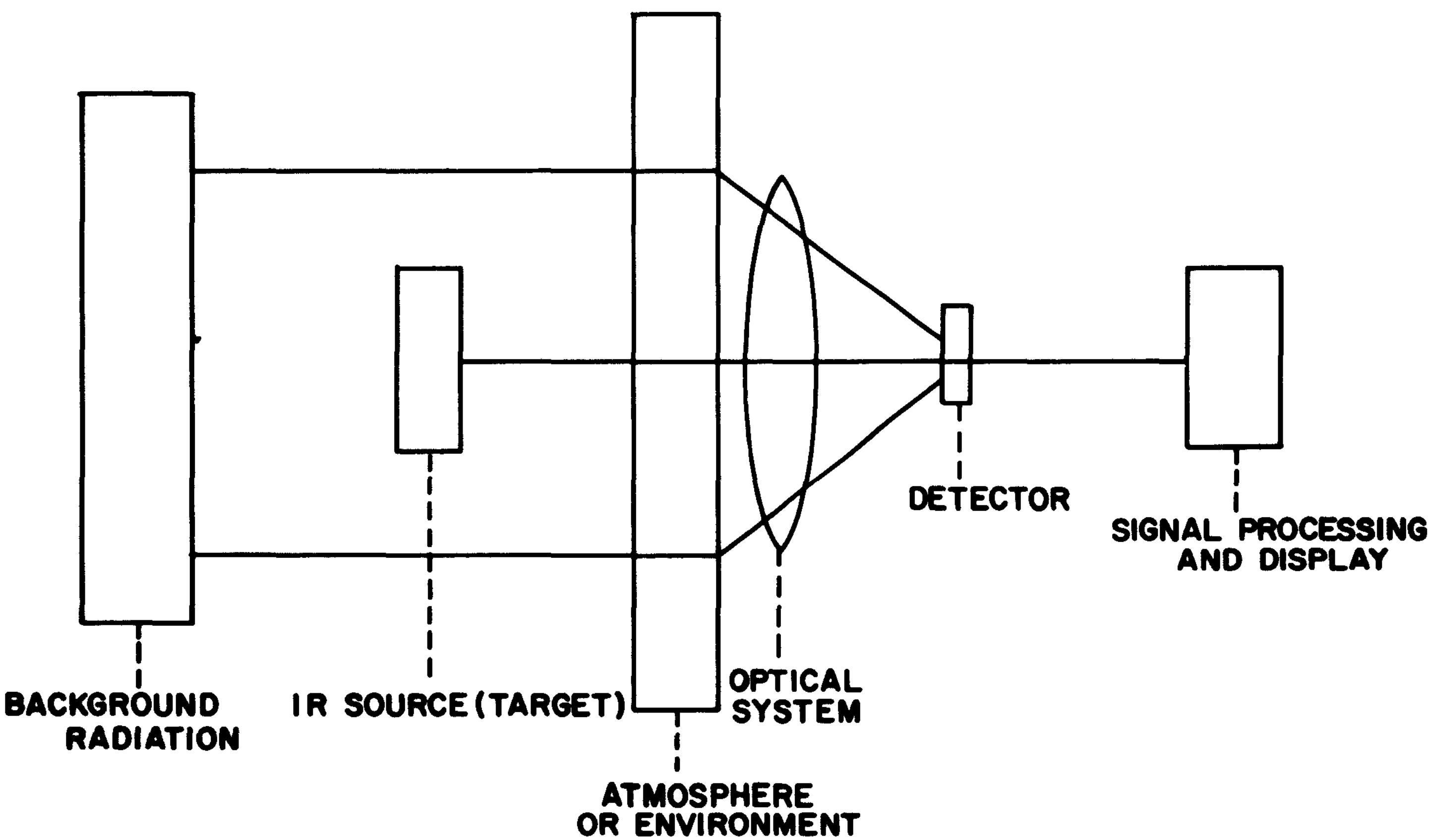


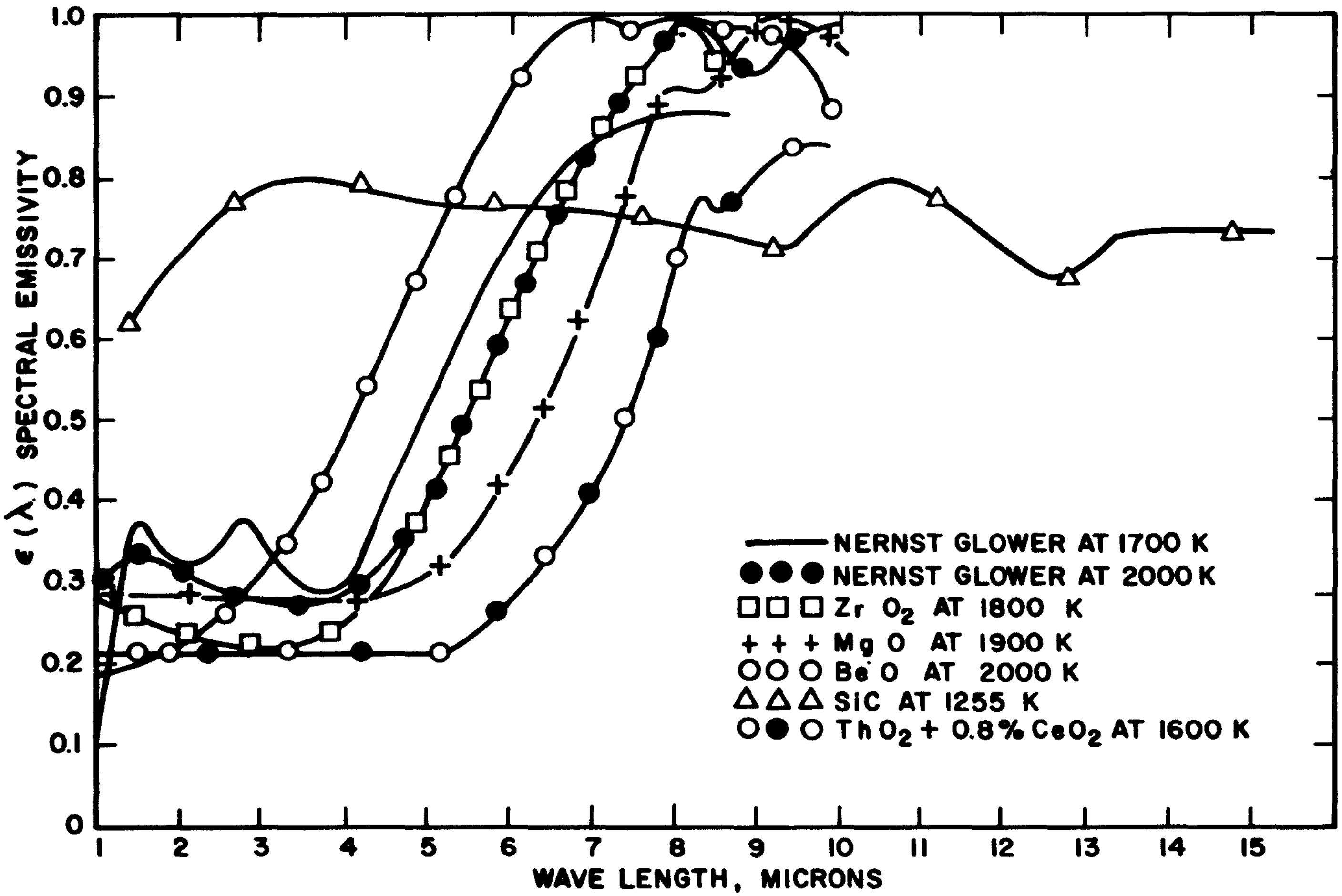
Figure 1. BLACKBODY SPECTRAL DISTRIBUTION CURVES

Figure 2. GENERALIZED IR SYSTEM[1]



[1] By permission from Infrared Radiation, by H. L. Hackforth. Copyright 1960. McGraw-Hill Book Company, Inc.

Figure 3. EMISSIVITY OF SEVERAL NONMETALLIC HIGH-TEMPERATURE MATERIALS[2]



[2] Neuringer, L. J. Electrical Manufacturing, vol. 65, no. 3, March 1960, p. 119.

transducer that transforms the incoming radiation into an electrical output; the output being displayed in a suitable manner to make the data available to the observer. (See Figure 2.)

IV. IR SOURCES

The sources of concern here are other than the "natural or background" sources (for as stated earlier, every object with a temperature above absolute zero emits IR radiation) and constitute generally the major ones in use today. Also not included are the commercially available blackbody sources which are used as controlled emitters.

The IR sources can be used to calibrate detectors and check theoretical predictions of a particular instrumentation. In the nondestructive testing of missiles, however, the missile case itself would be the IR source (target).

The sources are categorized and listed as follows:

Category I - Heated solids giving a continuous spectra.
Category II - Excited gases and vapors giving line spectra.
Category III - Luminescent materials giving line or band spectra.

It may be of interest just to mention another source of IR, the infrared maser, which is a fairly recent development.[3]

Before listing the major sources, Figure 3 is presented to give a general idea of the efficiency of several high temperature materials with respect to a blackbody.

Category I - The globar has a useful wave length range of approxmately 1.5 μ to 15 μ. It consists of a silicon carbide rod that is electrically heated to about 1200°C at 200 watts. The emissivity of the globar is nearly independent of wave length and is about 80% blackbody in the range given.

The Nernst glower has about the same wave length range as the globar. It too is an excellent source for its emissivity corresponds favorably to that of a blackbody (Figure 3). It consists of a rod or filament of zirconium and yttrium oxides and is heated by an electric current between 1500° and 2000°K. The glower generally operates in air, thus ending the problem of an IR transmitting window. However, temperature variations can occur due to a draft unless the filament is shielded.

The wave length range of the Walsbach mantle is about 15 μ to 150 μ. It is a gauze or mantle comprised of thorium oxide with a few percent cerium oxide added. The mantle is heated either by gas or electric current. At 15 μ, its emission is close to that of a blackbody at 2000°C, which is superior to most other sources.

[3] Schawlow, A. L. and Towns, C. H. Phys. Rev., vol. 112, no. 6, Dec. 15, 1958, pp. 1940-9.

The carbon arc is an excellent source in the wave length range of 10 μ to 100 μ where its output is stable to 2%. The advantage of a great gain in brightness over other sources is obtained.

A carbon rod heated electrically to a temperature of 2000°K, mounted in a water-cooled vacuum jacket with potassium bromide window, has been described.[4] The emission out to 10 μ is similar to that of the globar, but beyond this, the rod emission is superior rising to a peak at 12.5 μ.

The tungsten filament has a range of about 0.75 μ to 3 μ. Spectral characteristics of the emission from a number of commercial lamps have been measured.[5] The ordinary lamps operate at about 2900°K and act nearly as a blackbody. However, it is glass inclosed, which limits the emission to wave lengths of less than 3 μ. It is next to the carbon arc in brightness.

Category II - In the mercury arc, the excited mercury vapor exhibits about a dozen well-marked emission lines between 1 μ and 2.3 μ. An increase in the vapor pressure tends to broaden the lines into a continuous spectrum. Generally, the emission from gases at low temperatures and pressures are of little value except in the visible and very near IR.

The high pressure mercury arc has a useful range of 150 μ to 1400 μ. It is the chief far IR commercial source available. Usually it operates in a fused-quartz or fused-silica envelope.

Category III - By a suitable choice of luminescent materials, emission bands can be obtained in the near and middle IR regions. Infrared emission out to 3.5 μ has been reported (1953).

V. TRANSMISSION FACTORS

The transmission of radiant energy is always accompanied by some attenuation in the medium through which it travels and by filtering effects and transmission losses encountered in the optical system through absorption, refraction, and reflection. For example, the transmission of IR radiation through the atmosphere is accompanied by certain "windows" or areas of high transmission; while at the other wave lengths the radiation is absorbed or scattered to a high extent. This attenuation, however, changes as the temperature, pressure, water vapor present, etc., changes in the atmosphere. The data in Figure 4 is for an arbitrarily "clear" atmosphere under normal conditions.

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[4] Smith, L. G. Rev. Sci. Instr., vol. 13, 1942, pp. 54 and 63.

[5] Barnes, B. T. and Forsythe, W. E. Jour. Opt. Soc. Am., vol. 26, 1936, p. 313.

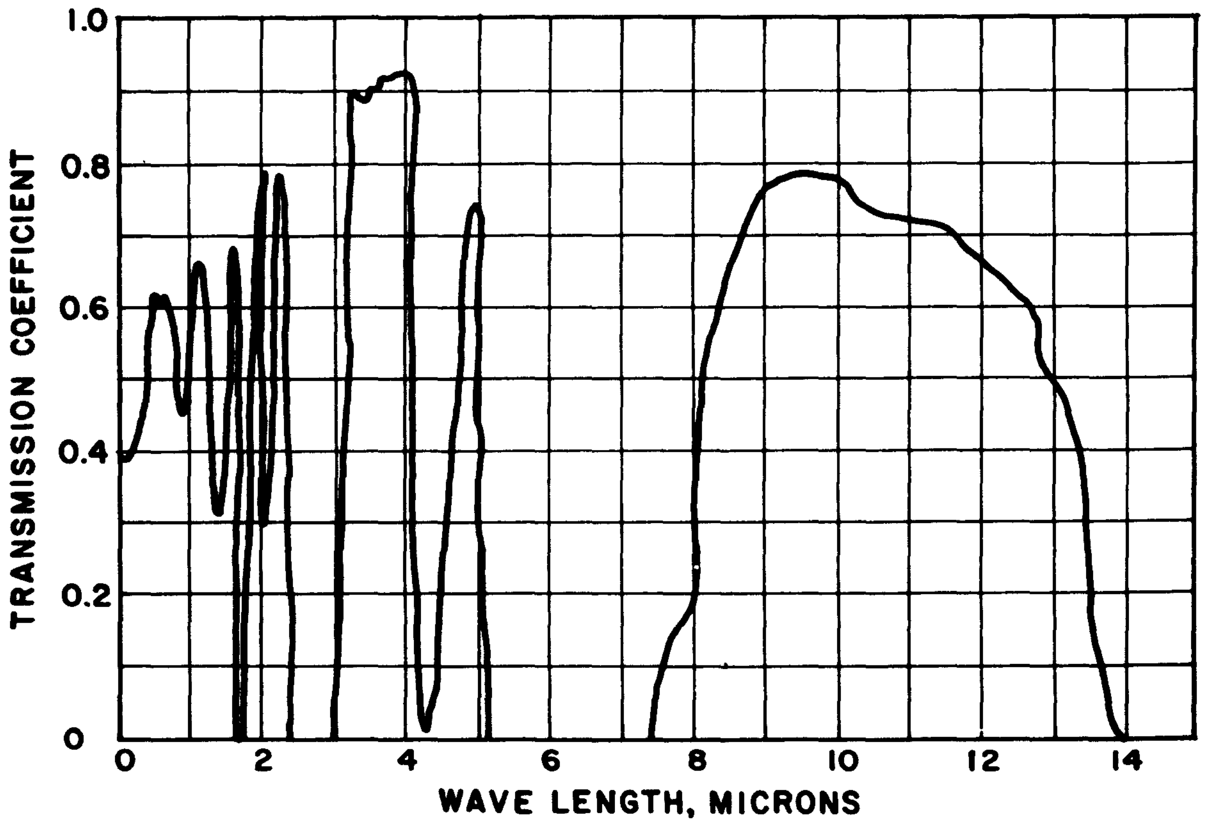

Figure 4. ATMOSPHERIC TRANSMISSION SPECTRA

In an instrumentation setup suitable for use in the nondestructive testing of rockets, the intervening atmosphere could be more or less controlled and its effects more accurately calculated; therefore, it would not be a serious consideration in obtaining information from the radiation signal.

VI. OPTICAL SYSTEM

The primary function of IR optics is to get the desired information (incoming radiation) to the detector with maximum efficiency.

Many special problems arise in designing an optical system for a given infrared instrument. One problem is due to the rather severe operating conditions, i.e., thermal stresses, strain, shock, etc., that are required in most applications. Another problem is in the fact that the IR region of the spectrum covers a much larger range of wave lengths than the visible portion of the spectrum, so that the physical properties (e.g., spectrally dependent properties such as refractive index) of the optical substances vary to a much greater degree. In fact, different optical materials must be used over different parts of the IR spectral range, while in the visible region, many varieties of glass and other common transparent materials are usable over the entire range.

Although there is today a wide variety of optical materials to choose from, the engineer must consider carefully the particular requirements he desires, and make compromises toward that end. As an example, in the near region of IR radiation ordinary glass with the visible light filtered out can be used without too much difficulty. However, the far IR region (greater than 10 μ) is the most critical region in selecting suitable materials.[6]

The major criterion in the choice of materials is that of high transmission (low absorption and reflection) characteristics. In some cases, antireflection coatings (black film coatings) are used to increase the transmission factor. In general, reflecting optical materials are used to replace refracting materials whenever possible as this eliminates internal absorption difficulties due to radiation travel through a lens. Of course, there are advantages and disadvantages to both reflecting and refracting optical systems which the designer must investigate in terms of his particular need (Table I).

Another component included in the optical system is the filter. The filter can be long-wave pass, short-wave pass, or band pass as required to transmit the desired wave lengths. In other words, there are particular wave length ranges or wave length bands for which the filter has high transmission. Optical filtering is also used to eliminate unwanted background

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[6] Wolfe, W. L. and Ballard, S. S. Optical Materials, Films, and Filters for Infrared Instrumentation. IRE Proc., vol. 47, no. 9, Sept. 1959.

Table I

ADVANTAGES AND DISADVANTAGES OF REFLECTING AND REFRACTING OPTICAL SYSTEMS[7]

Type of Optics	Advantages	Disadvantages
Reflecting	No selective absorption of IR radiation; high transmission; very high reflectivity of metal films; no chromatic aberrations; less spherical aberration than for a single refracting element. Long focal lengths possible in a compact optical system. Axial aberrations can be reduced by suitably located stop.	Reversal of image in single mirror. Curved focal surface. Field of view limited by off-axis aberations. Correction of abberrations requires introduction of refracting elements. Blocking effect of secondary mirror reduces optical gain. Mounting, environmental, and alinement problems. Difficult to shield from stray radiation. Window required to seal optical system introduces chromatic aberrations.
Refracting	More control of aberrations; greater freedom of design. No blocking factor; better image quality possible; wider-aperture, faster lens systems possible; mounting problems simpler; sealing window not required; less sensitive to thermal effects; alinement and focusing simpler.	More reflecting surfaces; selective absorption effects; wavelength transmission limitations of available materials; chromatic aberrations.

[7] By permission from Infrared Radiation, by H. L. Hackforth. Copyright 1960. McGraw-Hill Book Company, Inc.

radiation, i.e., the radiation from objects other than the desired source or target radiation, that can affect the system detector. If the spectral characteristics of the target and background are known, it is possible to choose an optical filter that will admit the target radiation, but have low transmission characteristics for the background radiation. Today there are many good optical filters which cover a wide range of wave lengths. Most of these eliminate by absorption, reflection, refraction, and interference.[8]

Figures 5, 6 and 7 present the general properties of some optical materials.[9] Transmission curves[10] of selected semiconductors and Polaroid type C infrared filters are presented in Figures 8 and 9, respectively. Transmittance plots[11] of wave length cutoffs of five materials and Bausch and Lomb interference filter series are presented in Figures 10 and 11, respectively.

Spatial filtering is used in an optical system for improving the ability of the target to be detected. This type of filtering permits the maximum conversion of the desired input radiation into the required output by eliminating the extraneous information. Spatial filtering is brought about by the use of fieldstops and/or choppers (reticles) at the necessary frequency to make the signal to noise ratio a maximum.[12]

Scanning techniques are very important in the choice of a proper instrument for the task at hand. The size of the object and the distance away, as well as the background radiation and the attenuation of the intervening medium, help determine the kind of scanning required. One can take the whole target or source into the field of view (image plane scanning - a second optical system samples this image point by point) or one can allow the instrument to move about on the target in various patterns, the form depending on the particular application and also the shape of the target (object plane scanning). Other parameters of the IR system such as detector time constant, total field of view, resolution, etc., generally limit the scanning system.[13]

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[8] Nichols, L. W. Optical Filtering. IRE Proc., vol. 47, no. 9, Sept. 1959.

[9] Aroyan, G. G. The Technique of Spatial Filtering. IRE Proc., vol. 47, no. 9, Sept. 1959.

[10] Holter, M. R. and Wolfe, W. L. Optical-Mechanical Scanning Techniques. IRE Proc., vol. 47, no. 9, Sept. 1959.

[11] Wolfe, W. L. and Ballard, S. S. Optical Materials, Films, and Filters for Infrared Instrumentation. IRE Proc., vol. 47, no. 9, Sept. 1959, p. 1541.

[12] Ibid., p. 1545.

[13] Nichols, op. cit., p. 1569.

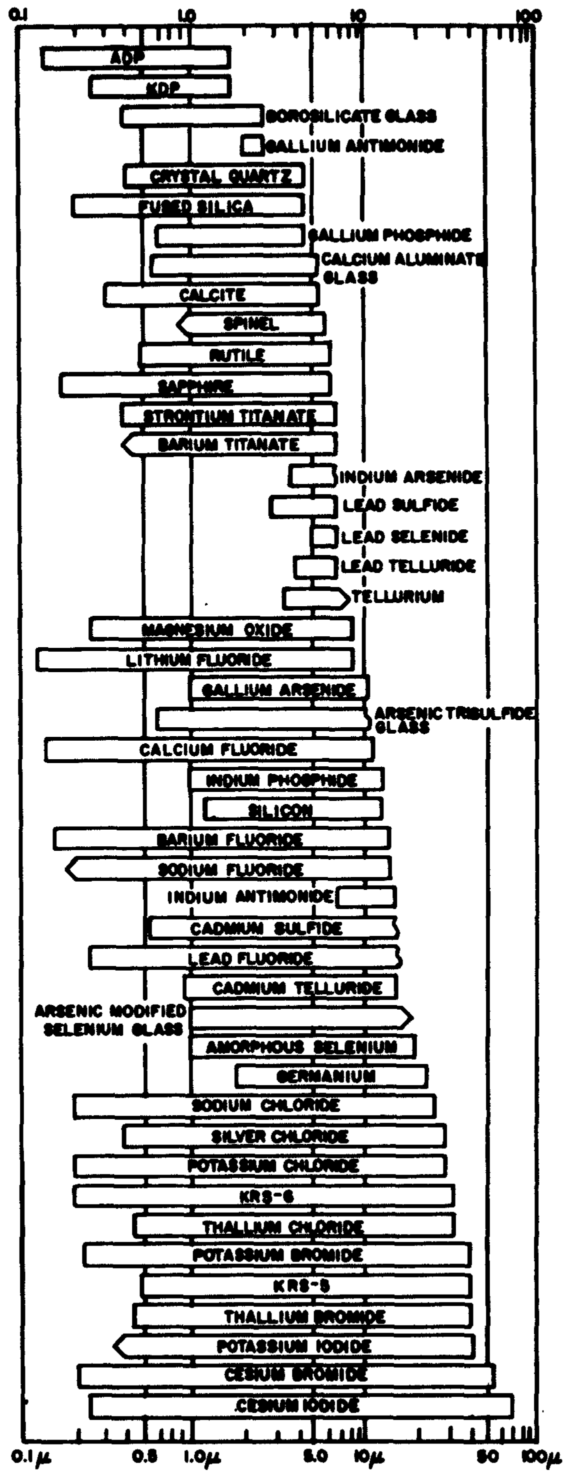

Figure 5. THE TRANSMISSION REGIONS OF SELECTED OPTICAL MATERIALS (Regions are for 10% transmittance or better, for a 2 mm sample at room temperature.)

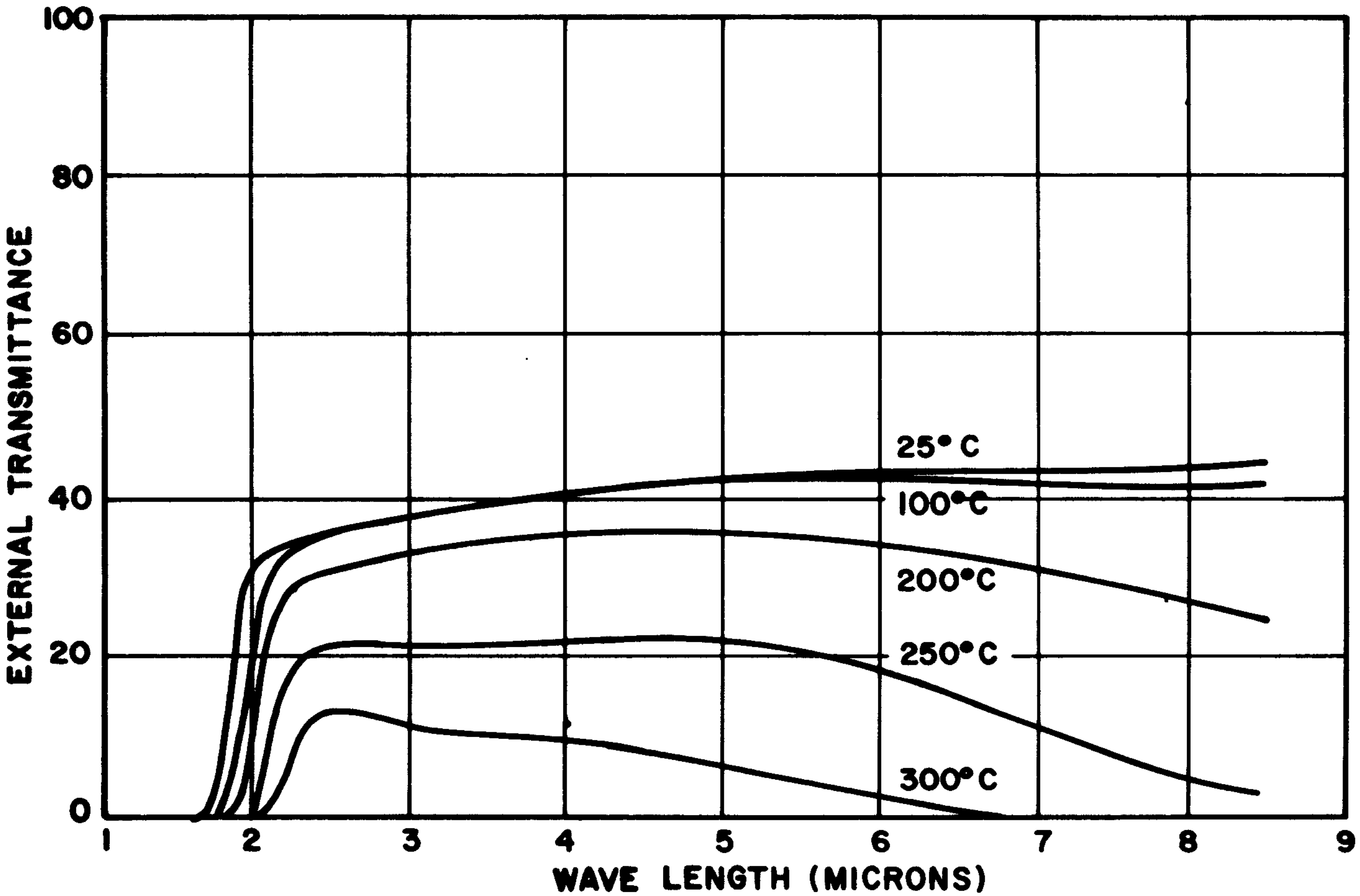

Figure 6. THE TRANSMISSION OF GERMANIUM FOR SEVERAL DIFFERENT TEMPERATURES; RESISTIVITY, 30 OHM-CM

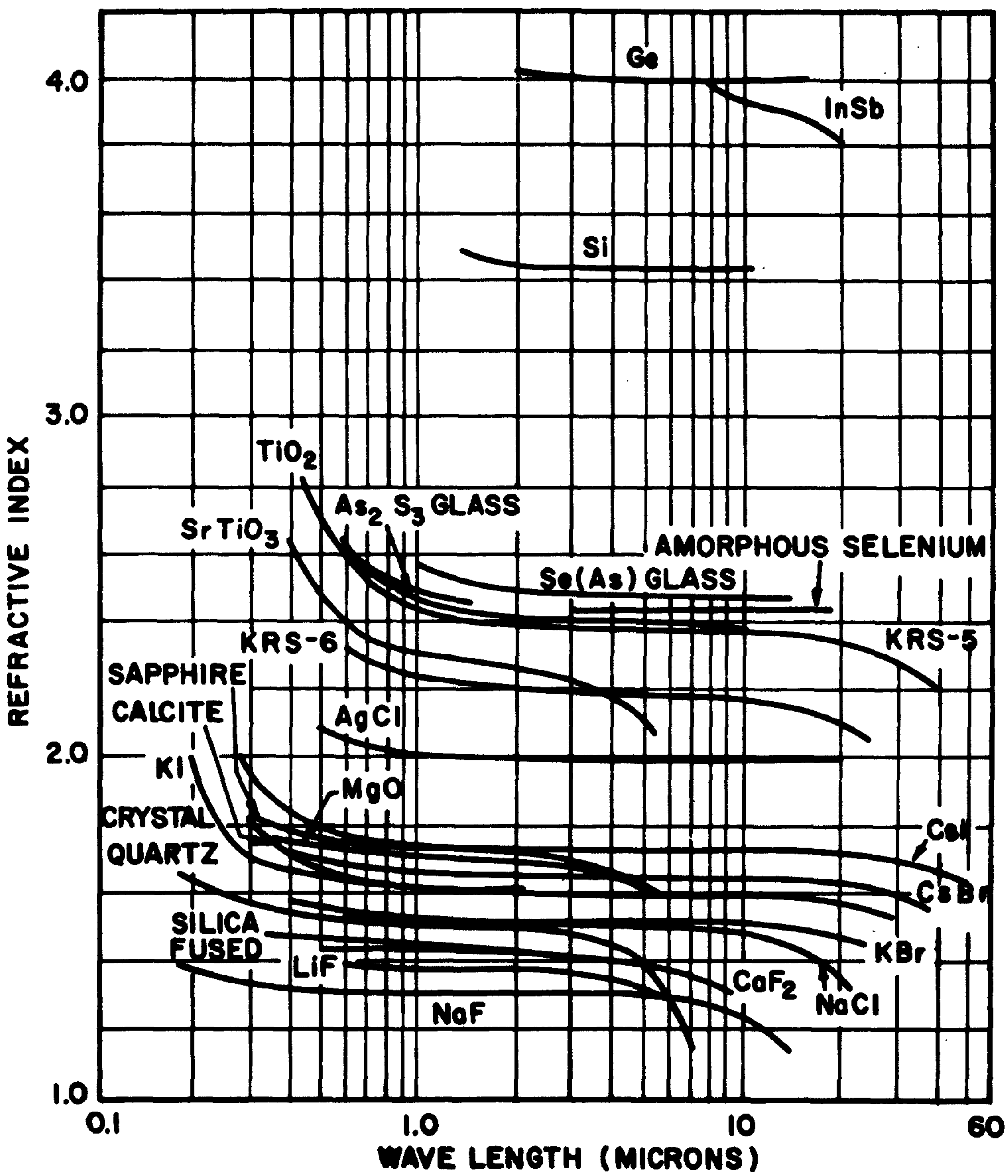

Figure 7. REFRACTIVE INDICES OF SELECTED OPTICAL MATERIALS

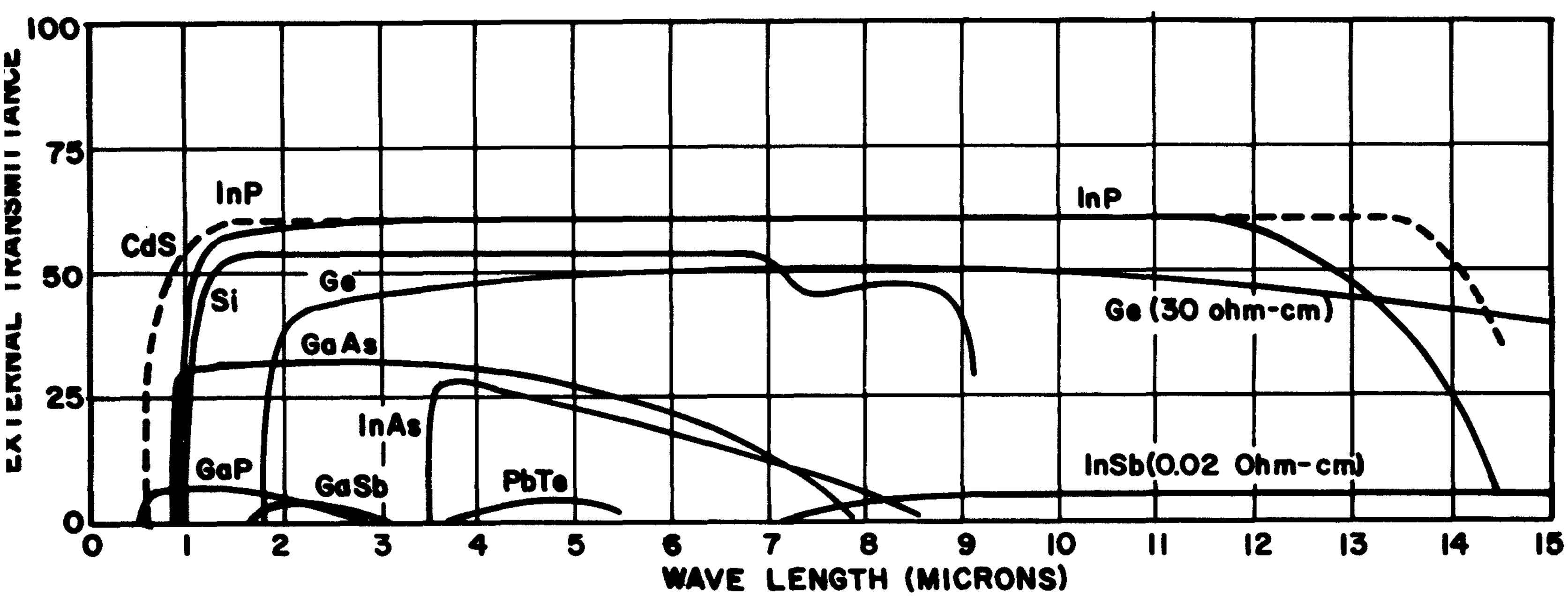

Figure 8. TRANSMISSION OF SELECTED SEMICONDUCTORS (Some data are derived from absorption constants; others are found in the literature. Resistivity is specified on some curves in ohm-cm.)

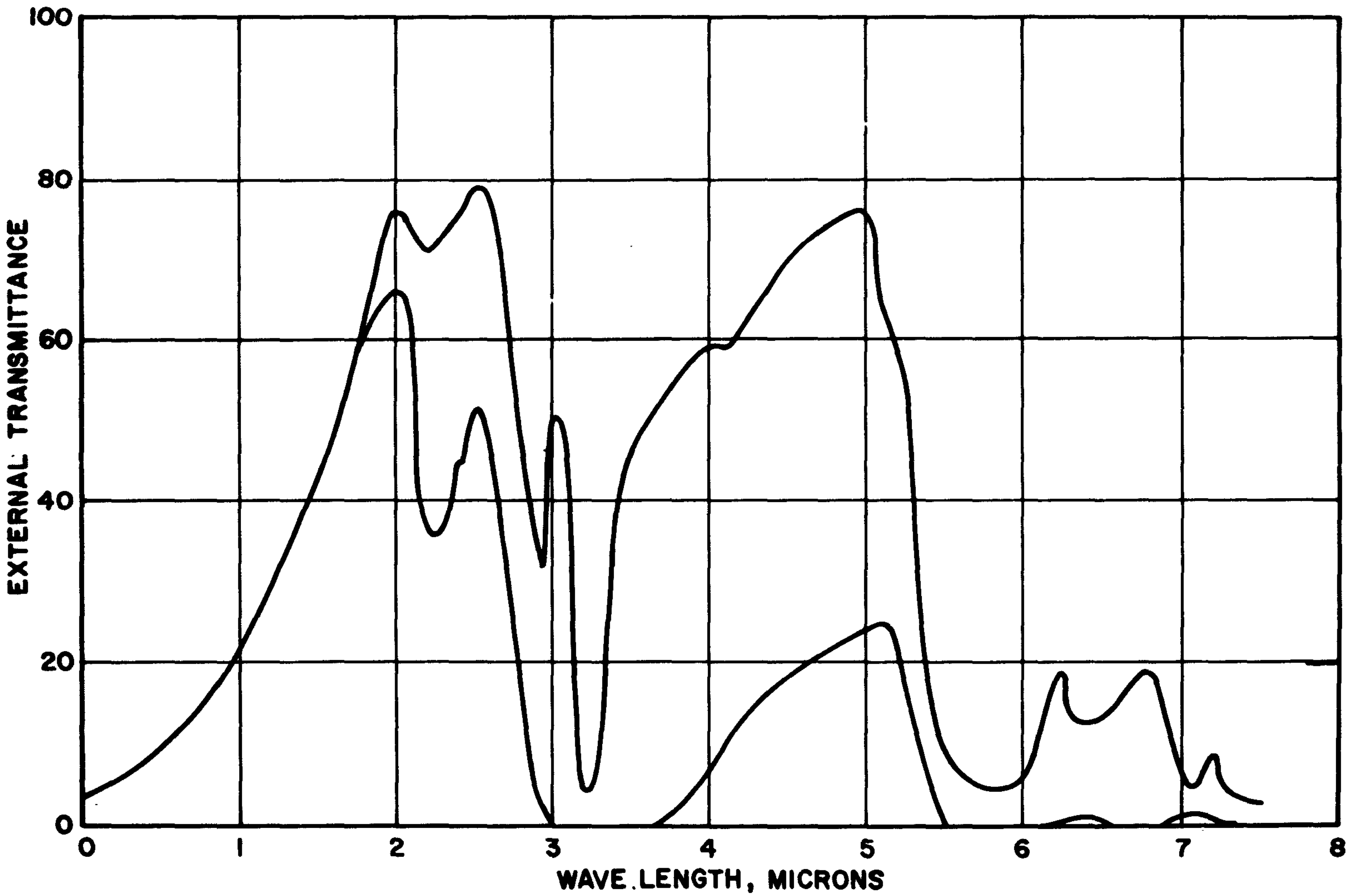

Figure 9. TRANSMISSION OF POLAROID TYPE C INFRARED FILTERS (The top curve presents the transmission of an unlaminated plastic filter, the bottom left that of a glass-laminated filter, and the bottom right, that of an unlaminated filter coated with a scattering mixture.)

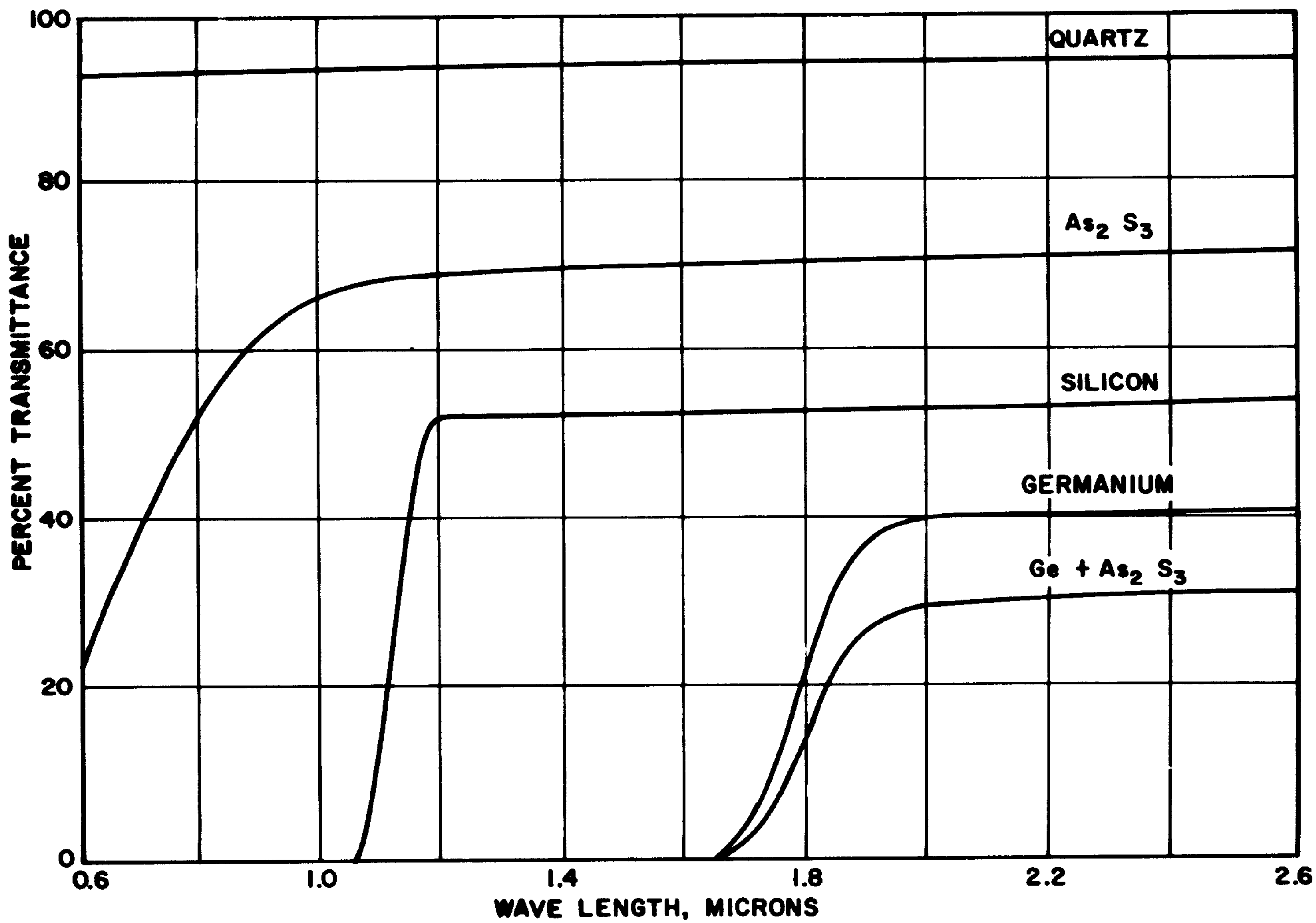

Figure 10. TRANSMITTANCE PLOT OF WAVE LENGTH CUTOFFS FOR FIVE MATERIALS: QUARTZ, As_2S_3, SILICON, GERMANIUM, AND Ge + As_2S_3

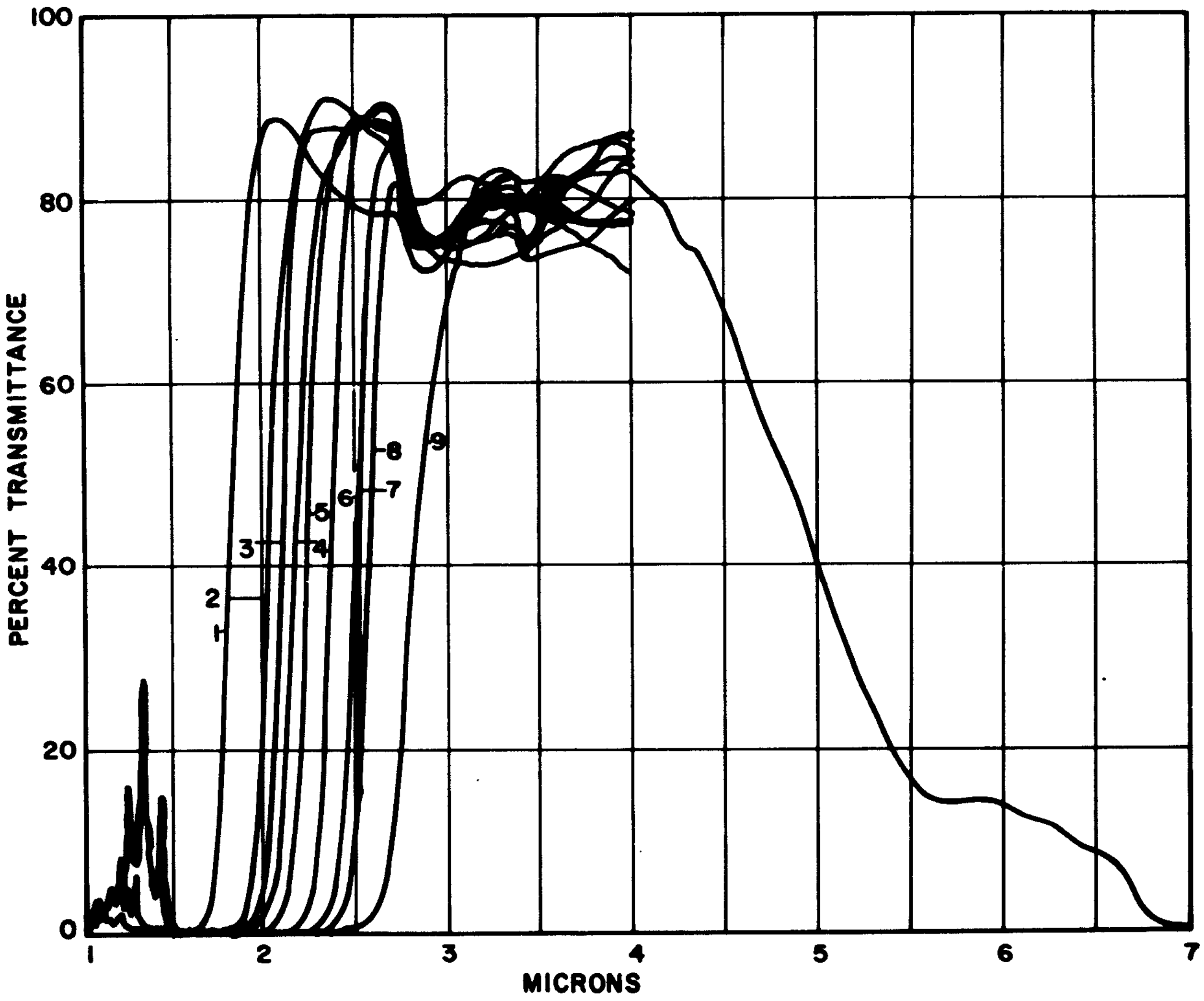

Figure 11. TRANSMITTANCE PLOT FOR BAUSCH AND LOMB INTERFERENCE-FILTER SERIES

VII. DETECTORS

The next component part of the IR system, which will be considered, is that of the radiation detector. As stated earlier, the radiation detector is an energy transducer, the input being radiant power and the output being, in general, an electrical signal. This field is developing rapidly and much work is going on in detector research and development. A brief synopsis will be given here on detector fundamentals and types.

There are two basic types of infrared detectors: the thermal detector, responding over the entire wave length region; and the photodetector, sensitive only over a limited wave length range. However, they have one fact in common; in each of the detectors, it is the electrical properties that are changed by the incident radiation. This is explained as follows. The crystal lattice of a solid is composed of atoms or molecules which constitute the solid and are characterized by lattice vibrations due to the temperature (they are sometimes called lattice phonons which are analogous to photons). The electronic system is characterized by a system of discrete energy levels. In thermal detectors, radiation is absorbed by the lattice causing increased thermal agitation (heating). This change in the temperature causes a corresponding change in the electronic system. Some examples of this type of detector are thermocouples and bolometers. In photodetectors, however, the radiation is absorbed directly by the electronic system to cause changes in the electrical properties. Some of the detectors of this group are the photoconductive, photovoltaic and the photoelectromagnetic (PEM) detectors. The photodetectors are primarily used for wave lengths beyond 1.5 μ. (See Table II.)

In general, the near IR region requires detector instrumentation similar to that used for the visible region. Thus photographic methods, infrared vidicons, photomultipliers, and photoemissive tubes are used. In the intermediate IR region, the most efficient detectors at present are the photodetectors. The far IR region, however, requires a device which changes one or more of its physical properties as a result of the temperature increase. (See Section VIII, p. 23.)

Detectors used in the IR region of the spectrum detect radiant power and not energy; therefore one cannot divorce sensitivity and the time of response of the detector. Photodetectors have much shorter time constants than thermal detectors. The sensitivity is defined as the amount of radiant power falling on the detector to give a rms electrical signal equal to the rms value of the noise introduced by the detector. This is also termed "noise equivalent power" (NEP). A bandwidth of unity is assumed in the circuit. The sensitivity is limited by the recorded fluctuations of the output, or as this is termed,

Table II

ADVANTAGES OF IR DETECTOR TYPES[14]

Detector Type	Advantages
I. Photoelectric cells, including photoemissive, some photoconductive, photovoltaic cells; dielectric cells, thalofide cells; photographic plates; phosphors and phosphor cells. Image conversion tubes........	Superior responsivity in the visible and near IR spectral regions; large signal amplification possible in photomultiplier cells.
II. Photoconductive cells	More responsive to lower temperature sources; superior detectivity in intermediate-IR spectral region; faster time constants; faster recovery from transients; may be directly coupled to preamplifiers.
III. Thermal detectors...........	More responsive to low-temperature sources; responsive over wide wave length bands, in the far IR spectral region detect greater fraction of the total IR radiation than photocells; mechanical chopping often not required; cooling of detector to low temperatures generally not required.

[14] By permission from Infrared Radiation, by H. L. Hackforth. Copyright 1960. McGraw Hill Book Company, Inc.

the "noise" of the detector.[15] The noise can be divided into two categories, which are additive in the detector output: the fluctuations of the incident radiation, and the noise inherent in the operating conditions.

Only recently have detectors been developed whose sensitivity is limited only to the fluctuations of the incident radiation falling on the sensitized surface and not other forms of physical interference (mechanical, electrical, etc.). These detectors are termed background limited. The noise properties of the detector are one of the primary considerations in selecting a detector for a particular instrumentation. The various noises have been investigated (see Section VIII, Item M, p. 24) and named according to the physical source that gave rise to it. The development of more sensitive, faster, more reliable detectors, i.e., detectors with low noise, is one of the greatest factors in the increased development of IR technology.

One of the factors that influences the inherent noise in a detector will be considered. For example, in the case of the photoconductive detector, a rise in the cell temperature causes a corresponding decrease in cell resistance and therefore increases noise. It is usually necessary, therefore, to cool the detector by the use of liquified gases, although research is being done to develop photoconductors that will not require sophisticated cooling methods (e.g., the use of dry ice instead of liquid nitrogen).

The impurity photoconductive detector has been developed and there are available several types with very high detecting ability in the 8 to 13 μ region. Impurity photoconductive detectors are prepared by the addition of other elements to the primary one. For example, impurity activated Ge detectors have been prepared by the addition of Cu or Cd to Ge. Another factor in the photoconductive detector is that of d.c. bias voltage; for an increase of this bias across the cell increases the current and hence the noise. Finally, the cell area in a photoconductor must be as small as possible to cut down noise. Other detectors have corresponding defects due to operating conditions which must be taken into account in their choice.

Examples of the detectors suitable for the different regions are listed and described in the following pages. Of course, the listed detectors are not rigidly limited to the wave length region given and overlap considerably.

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[15] Jones, R. C. Performance of Detectors for Visible and Infrared Detectors. Advances in Electronics, vol. V. Academic Press, Inc. 1953.

VIII. INFRARED DETECTORS

The IR detectors listed from A through E are photodetectors (with the exception of E) and are primarily used in the near IR region. Detectors F and G are used in the middle region of the IR spectrum; they too are photodetectors. H through L are thermal detectors which are used in the far IR region.

A. Photoconductive Detectors

An "internal" photoelectric effect takes place, i.e., free electrons are produced in the interior. The operation depends on resistance changes upon illumination by IR radiation. The long wave length limit is usually 7 to 8 μ; however, detectors have been made that are sensitive out to 40 μ.

B. Photodielectic Detectors

The dielectric constants change in some materials upon irradiation with different wave length energy.

C. Photoemissive Detectors

The IR radiation incident on the sensitive part of the detector cell causes an electron stream due to photoemission. The secondary emission of a photomultiplier tube then multiplies the incident electron stream.

D. Thallium Sulfide Photovoltaic Cells

Sandwiched between two layers of conducting material (thallium and gold or platinum) is a high resistance photosensitive layer. When the cell is exposed to IR radiation, a photovoltage is produced.

E. Photographic Emulsion Detectors

The photographic emulsion consists of various silver halides deposited in granular form within a gelatin. Upon the absorption of an IR quanta, an electron is released which activates the emulsion halide.

F. Photoconductive Cells of the Lead Salts

1. Lead Sulfide Photocells

Thin activated layers of lead sulfide show a marked resistance change when irradiated with IR. These cells have an upper cutoff of about 4 μ and are cooled with liquid nitrogen.

2. Lead Telluride Photocells

These cells have properties similar to those of lead sulfide. These too are cooled with liquid nitrogen and have a cutoff of 5.5 μ.

3. Lead Selenide Photodetectors

These are liquid nitrogen cooled with cutoff at 5.4 μ.

G. Photoelectromagnetic (PEM) Detectors

The PEM effect is observed when a slab of semiconductor, irradiated perpendicular to one of its surfaces, is placed in a magnetic field perpendicular to the direction of illumination. An emf appears in the third perpendicular direction. This type of cell has a great advantage of sim licity, for it operates at room or dry-ice temperatures.

H. Thermocouples and Thermopiles

A circuit consisting of two dissimilar materials in contact is maintained at different temperatures and an emf is developed.

I. Bolometers

It absorbs incident radiation on a thin blackened surface and the slight heating causes a change in the resistance. This is detected by measuring the voltage change in the circuit setup. A small change in the incident can thus be noted.

J. Golay Pneumatic Cell

A gas-filled cell that contains a very thin radiation receiving membrane. The heating of this diaphragm causes expansion of the gas in contact with it.

K. Thermistors

The operating principle is the resistance variations in certain thermally sensitive resistors.

L. Nonlinear Phosphors

The variant physical property is a change in the luminescence of the phosphor.

M. Detector Noise

1. Johnson noise - small voltage changes due to the thermal fluctuations of the electrons. This factor occurs in all IR detectors.

2. Current noise - the extra noise above that of Johnson's that appears across a resistor when a current passes through it. It is most noticeable in resistors and semiconductors made from compressed powders or deposited films.

3. Shot noise - it is noise caused by the random thermionic emission of electrons. It appears in thermionic detectors.

4. Temperature noise - fluctuations in thermal detectors caused by the heat energy interchange between the detector's sensitive surface and its immediate environment.

5. Generation-recombination noise - caused by the Fermi-Dirac fluctuation of electrons in photoconductive cells and bolometers.

6. Modulation noise - fluctuation in the resistance of semiconductors.

7. Flicker noise - this appears in thermionic detectors and is caused by the random variations in electron emission from the cathode.

IX. OUTPUT DATA

Infrared instrumentation for interpretation of detector parameters can be broken down into two general types: the image-forming system,[16] which is capable of producing a visible, two-dimensional representation of the output (intensity differences), and the nonimage-forming system;[17] e.g., the radiometer detector, which collects IR radiation and focuses it onto a detector. The detector, with a suitable electronic circuit, converts it into an electrical signal.

Information about the target and surrounding scene is available in the form of incoming radiation. The ultimate efficiency of the detector output, in either type of system, is set by the detector's inherent noise characteristics due to the imperfections in the IR system and the statistical fluctuations in the radiation received. In the image-forming system, a limit is also set by the ability of the observer to perceive intensity differences.

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[16] Weihe, W. K. Classification and Analysis of Image-Forming Systems. IRE Proc., vol. 47, no. 9, Sept. 1959.

[17] Jamieson, J. A. Special Electronic Circuits for Nonimage-Forming Infrared Systems. IRE Proc., vol. 47, no. 9, Sept. 1959.

X. PRESENT STATE-OF-THE-ART IN IR NONDESTRUCTIVE TESTING OF MISSILES

With infrared technology as a background, the various IR nondestructive testing projects mentioned in the Section I, "Introduction" will be considered along with some recommendations and conclusions.

The first project that will be considered is Perkin-Elmer Corporation's TIRI (Thermal Infrared Instrument), a laboratory device. TIRI is an active system (see Section III), consisting of an R-F (450 kc) induction heater, a modified lathe table on which the test samples are placed, a Perkin-Elmer radiometer, and a readout.

Test samples were provided by AMC Projects Office to determine the feasibility of the system. The test samples provided were cylinders five inches in diameter and about one foot long. They were constructed to simulate an actual solid fuel rocket motor and thus had the corresponding liner and inert propellant. The test samples had built-in, inch-wide unbonded strips running parallel to the axis for the full length of the cylinder. There were both first and second interface unbonds, and in one of the test samples, these were overlapping. Of course, some of the cylinders had no unbond flaws included. These were for comparison purposes.

The lathe table allows for a spiral scan path along the surface of the cylindrical test sample. The R-F heat sources is fixed, the gap between the test sample and heat source being set arbitrarily to give the desired heat input and hence better results. The gap was quite small, on the order of 0.070 inches and consequently could be a disadvantage in testing an actual rocket motor with clips or other protrusions on the surface. A mirror set at a 45° angle, from the axis of the test sample, is fixed at a 90° radial arc from the heat source above the surface of the sample and reflects the radiation into the radiometer. The mirror can be adjusted axially, i.e., along an axis parallel to the test sample axis, thus determining the time difference between heating and detection. A Perkin-Elmer radiometer is focused on the mirror. The readout used at present is a strip-chart recorder, with the signal level in the positive Y (ordinate) direction indicative of temperature. A blip or "bump" means a sudden increase in temperature and indicates an unbond flaw. The position of the signal blips in all cases with the samples tested conformed to the actual flaws in the sample.

Plans are under way at present to use the TIRI instrumentation, after suitable hardware modification, on actual rocket motors. As yet, however, the TIRI instrument has been used only along the cylindrical length of the rocket motor, and not the dome end which is of much interest. It is recommended that suitable means be taken to explore the dome end for unbond flaw.

A second research and development project in the realm of IR nondestructive testing of solid fuel rocket motors is being carried on by Lockheed at Palo Alto.

This is a passive system, with the instrumentation detecting the natural radiation being emitted by the rocket motor case. The rocket case or test object is subjected to a "heat soak" method of heating, i.e., the test object is placed in a conditioning chamber for a suitable length of time until it is in thermal equilibrium, and then taken out into an ambient temperature environment. The method in use thus far involves only the heating of the test object above ambient; however, it would possibly be advantageous to cool the test object <u>below</u> ambient temperature.

The IR instrument was initially designed as a laboratory instrument to determine test parameters. The optical system of the instrument consists of two stages separated by a chopper (reticle). The first stage system is reflective with perforated mirrors to collect, focus and transmit the incoming radiation to the chopper plane. The blades of the chopper are heated by a blackbody source to the mean temperature of the missile case, and consequently, the detector sees the difference between this signal and the input signal; thus the second optic stage behind the chopper is similar to the first stage. It collects and focuses radiation from the plane of the chopper to the detector.

The detector is a thermistor bolometer with a germanium window. A specially designed preamplifier and main amplifier are used to amplify the detector signal. The display of data can occur in two ways. The output of the main amplifier is calibrated to read microvolts input to the preamplifier. Also the output voltage can be recorded on a Sanborn Model 650 optical recorder. Of course the output voltage variation is proportional to the temperature to the temperature variation.

It appears feasible that although this instrument is being used primarily to detect unbond in fiberglass-wound rocket motor cases, it would be able to detect similar flaws in steel motor cases. It would be more difficult, however, due to the superior thermal conductivity of metal (the signal would tend to be washed out more rapidly) and the inferior emissivity of the steel case to that of the fiberglass case, where the emissivity factor is more uniform and of a higher magnitude, The actual optimum conditions for a steel case motor have not as yet been determined. Unbond flaws in fiberglass rocket motors can be detected by the instrument. At present, however, it is not possible to determine the depth of the flaw, i.e., first interface unbond as opposed to second interface unbond, etc.

It would be advantageous to set up some preliminary tests on actual steel-cased rocket motors for purposes of correlation and comparison between the passive and active systems of instrumentation.

Two other companies with government contracts in the field of IR nondestructive testing have been investigated. Automation Industries, Research Division, Boulder, Colorado has an active system IR instrumentation. The test instrument consists of a commercial radiometer (thermodot Model TD-5) mounted on a tripod so that it can be focused at any distance from the heat spot, an oscilloscope readout with temperature variation being shown, a heat source (1000 watt Sylvania projection lamp), and a scan table that runs on tracks with variable speed and also position, which had a motion perpendicular to the direction of the tracks. The scanning is, therefore, accomplished by holding the heat source and radiometer in fixed positions and moving the scan table. This is, of course, for flat test samples.

Tests were planned and conducted with the cooperation of the test engineer at Automation Industries on a fabricated flat plate test sample provided by AMC with known unbonds built in at both the first and second interfaces. The results were not conclusive, however, and further tests are advisable.

Thiokol made an investigation of the possibility of using commercially available IR instruments for unbond flaw detection in steel-cased motors.

The conclusion reached was that suitable modification is needed before it would be feasible to use commercially available instruments for IR nondestructive testing of missile unbond.

To reiterate, it is certain that the general feasibility of IR techniques and instrumentation has been proven on a laboratory scale. What is needed, however, is an IR device specifically for use on actual missiles to prove its ultimate feasibility and practibility.

XI. CONCLUSIONS

It suffices to say that this field of technological endeavor is so recent in its application to nondestructive testing, that it assuredly had a long future of development. It appears that there are advantages and disadvantages with both the active and passive IR instrumentation systems. The active system has the advantage of more controlled heating during the test run, but inherently requires a more complex instrumentation than the passive system because of the heat source. There is a definite need for a portable field instrument for nondestructive missile testing and passive systems seem much more suitable. However, in both systems, the major disadvantage at present is that of limited versitility, so that the IR instrument must be designed more or less specifically for the problem at hand.

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